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TRANSMITTAL OF A PATENT APPLICATION

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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

INVENTOR(S): Stephen Griffin

TITLE: OPTICAL FIBER WITH NUMERICAL APERTURE COMPRESSION

The Commissioner of Patents and Trademarks
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TRANSMITTAL OF A PATENT APPLICATION
(UNDER 37 CFR § 1.53)

JC560 U.S. PTO
09/14/98
09/01/98

Transmitted herewith is the above identified patent application including:

- ☒ Specification, claims and abstract, totaling 30 pages.
- ☒ Formal drawings, totaling 3 pages.
- ☐ Informal drawings, totaling _____ pages.
- ☐ Information Disclosure Statement.
- ☒ Declaration and Power of Attorney.
- ☐ Assignment(s) to _____
- ☒ A verified statement to establish Small Entity Status under 37 CFR 1.9 and 37 CFR 1.27.
- ☐ Other: _____

FEE CALCULATION (for a small entity)

Fee Items	Claims Filed	Included w/basic fee	Extra Claims	Fee Rate	Total
Total Claims	34	+20	14	x \$11	154.
Independent Claims	3	+ 3	-0-	x \$41.	-0-
Mult. Dependent Claim Fee (one or more)				x \$135.	
Assignment Recording Fee				\$40	
Basic Filing Fee				\$395.	395.
TOTAL FEES					549.00

☒ A check in the amount of \$ 549. to cover the filing fee and ☐ assignment is enclosed.

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1 OPTICAL FIBER WITH NUMERICAL APERTURE COMPRESSION

2
3 BACKGROUND

4 In the fields of spectroscopy and surgery, optical fibers
5 employing laser inputs are increasingly being used. For surgery,
6 optical fibers are often used in illumination of body cavities,
7 imaging those cavities and in delivering laser energy for
8 incision/excision, coagulation, homeostasis, and vaporization of
9 tissue. Typically, the optical fibers which are used require a
10 relatively high Numerical Aperture (NA) in order to capture as high
11 a percentage as possible of the optical energy available from the
12 laser source. High NA fibers, however, result in relatively wide
13 divergence of the light spots at a relatively short distance from
14 the ends of the fibers. Such divergence is not permissible for
15 many applications; so that relatively expensive and cumbersome lens
16 systems have been attached to the output ends of such fibers in
17 order to focus or collimate (or nearly collimate) the light exiting
18 from the output end of the fiber. Such lenses must be added to the
19 fiber end as a separate manufacturing step, and tend to cause the
20 endoscope (or spectroscopic probe tip) to be larger and more
21 invasive than would be the case if such lens systems were not
22 required.

23 Surgical fibers for energy delivery often are damaged in use,
24 due to inadvertent contact with the target tissues. Contamination
25 of the fiber output with tissue causes localized heating and
26 consequent damage to the fiber, reducing the output beam quality.

1 The wide-angle divergence of energy from high NA fibers
2 contributes to this failure, in that the surgeon, in his search for
3 the energy density he desires for the sought tissue effects, often
4 inadvertently overshoots. This results from the fact that the high
5 energy densities are found only very close to the fiber output; so
6 unintended fiber/tissue contact is likely.

7 With lower NA output of a fiber, energy densities do not fall
8 off as quickly; so that fiber/tissue separation of greater
9 distances can be attained. Lower NA fibers are often incompatible
10 with the launch NA of laser sources (and other, e.g. white light
11 sources) used. A common additional problem is the minimum focal
12 spot size of sources being larger than the optimum fiber core
13 diameter. Typically, tapered fibers are used where the desired
14 fiber is smaller than the minimal launch focal spot. While
15 inefficient (typically 65%), these arrangements are often
16 acceptable in many applications.

17 A popular pulsed Holmium doped yttrium-aluminum Garnet crystal
18 laser (Ho:YAG), used in laser lithotripsy has a minimum focal spot
19 size of approximately 300μ M diameter. 300μ M core fiber,
20 however, is often too stiff to reach easily through small, highly
21 twisted lumen of the type encountered in a human ureter, the
22 location of the calcium carbonate kidney stones that lithotripsy is
23 designed to treat. The maximum power of the laser, however,
24 exceeds the minimum energy required to break up the stones; so that
25 a surgeon is content with inefficient delivery if some means can be
26 devised to get at least some significant portion of the laser

1 energy into a smaller core fiber. It is desirable to use a smaller
2 core fiber in order to achieve the flexibility not attainable with
3 a 300 μ M core diameter.

4 Other applications, such as assemblies for performing
5 diagnostics, for example, identification of cancerous versus non-
6 cancerous tissues by Raman spectroscopy also are increasingly
7 utilized. In spectroscopy, several basic configurations exist with
8 applications in absorption/transmission, and fluorescence
9 (including phosphorescence and Raman spectroscopy). A single fiber
10 may be used to deliver and collect reflected or scattered energy
11 when external optics are used to split the signal return and the
12 excitation signal.

13 The basic fiber configuration typically includes a relatively
14 high NA excitation fiber, which is uniform throughout its length.
15 The path length for the absorption spectroscopy measurement then is
16 determined by mounting the fiber in a threaded carrier tube, with
17 a mirror on an attaching cap spaced a distance one-half that of the
18 desired path (due to the reflection of the mirror causing the light
19 to transverse the space twice). Ideally, collimated or nearly
20 collimated light (consistent with low NA fiber) is desired from the
21 exit end of the excitation fiber; so that a maximum return of light
22 is available for the return path. However, this is inconsistent
23 with high NA fibers designed to capture the maximum light energy
24 available from the source.

25 In spectroscopy, dual fiber devices or multiple fiber devices
26 also may be employed, with one fiber being used as the excitation

1 or illumination fiber and the others arranged in close proximity or
2 surrounding the excitation fiber comprising the detection or
3 collection fibers. Many of the same problems which exist with
4 surgical applications also apply to these fiber optic spectroscopy
5 devices. At the output end of the excitation fiber, it is
6 desirable to have the light exit in a collimated or near collimated
7 form. For high NA fibers, however, a relatively wide angle of
8 light rays exit the end of the fiber; so that there is a relatively
9 large circle of light or scattering at a relatively short distance
10 from the fiber end. To overcome this, separate lens systems may be
11 applied to the end of the fiber. These lens systems present
12 additional complications in spectral performance in addition to
13 those previously noted.

14 It is desirable to provide an optical fiber capable of NA
15 compression or reduction of the excitation fiber output, which is
16 simple to manufacture, and which effectively reduces the NA between
17 the input end of the fiber and the output end.

18 19 SUMMARY OF THE INVENTION

20 It is an object of this invention to provide an improved
21 optical fiber with Numerical Aperture compression.

22 It is another object of this invention to provide an improved
23 illumination optical fiber with Numerical Aperture compression
24 using an outwardly flared conical taper at the output end of the
25 fiber.

26 It is another object of this invention to provide an improved

1 Numerical Aperture compression device which tends to collimate the
2 light exiting an optical fiber.

3 It is a further object of this invention to provide an
4 improved optical fiber with Numerical Aperture compression in which
5 the output end of an excitation fiber has an outwardly-flared,
6 uniform conical taper on it with a length substantially greater
7 than the diameter of the widest portion of the taper.

8 In accordance with a preferred embodiment of the invention, an
9 optical fiber with Numerical Aperture compression is comprised of
10 a tapered fiber section. The tapered fiber section has a pre-
11 established length, with an input end having a first predetermined
12 diameter and an output end of a second predetermined diameter,
13 greater than the first predetermined diameter.

14 BRIEF DESCRIPTION OF THE DRAWINGS

15 Figure 1 is a diagrammatic representation of a spectroscopy
16 system using fiber optic components;

17 Figure 2 is a representation of a typical fiber optic probe of
18 the type used in the system shown in Figure 1;

19 Figures 3 and 4 are cross-sectional side views and cross-
20 sectional end views, respectively, of prior art devices used in the
21 systems and probe of Figure 2;

22 Figure 5 is a cross-sectional representation of a preferred
23 embodiment of the invention which is to be substituted for the
24 prior art devices of Figures 3 and 4;

25 Figure 6 is a diagrammatic representation of reflected light
26

1 rays of the embodiment shown in Figure 5;

2 Figure 7 is a cross-sectional view of a surgical probe
3 incorporating the preferred embodiment of the invention shown in
4 Figure 5;

5 Figures 8 and 9 are partial cross-sectional side views of
6 absorption spectroscopy probes using the preferred embodiment of
7 the invention shown in Figure 5;

8 Figure 10 is a variation of the probe shown in Figure 2 used
9 to incorporate structures of the preferred embodiment of the
10 invention shown in Figures 5 and 6;

11 Figure 11 is a diagrammatic representation of a variation of
12 the invention shown in Figure 5; and

13 Figures 12 and 13 are cross-sectional side views and end
14 views, respectively, of a variation of the embodiment of the
15 invention shown in Figure 12.

16
17 DETAILED DESCRIPTION

18 Reference now should be made to the drawings, in which the
19 same reference numbers are used throughout the different figures to
20 designate the same components. Figure 1 is a diagrammatic
21 representation of a typical light-scattering spectroscopy probe
22 system using a bifurcated fiber probe of the type illustrated in
23 Figure 2. Systems of this type are employed in various types of
24 spectroscopy, such as absorption/transmission spectroscopy,
25 fluorescence spectroscopy and light scattering spectroscopy. An
26 optical source, such as a laser 10, supplies a beam of light to a

1 beam splitter 12, with a portion of the light beam then being
2 applied through a focusing lens 14 to the end of a fiber optic
3 coupler 16. The coupler 16 is connected to the input end of an
4 optical fiber 18, which preferably is a silica-clad silica core
5 (si/si) fiber. Although other optical fibers are available, such
6 as polymer-clad silica fibers (PCS), such fibers typically have an
7 unacceptably high intrinsic fluorescence which precludes their use
8 in light-scattering spectroscopy probes. The excitation energy
9 carried by the fiber 18 is supplied to a probe 20, which is
10 immersed in a sample 22. Often, the probe 20 is provided with a
11 mirrored cap to space a mirror a pre-established distance from the
12 end of the optical fiber 18. Such caps (not shown in Figure 1)
13 have apertures in them to allow the fluid of the sample 22 to pass
14 into the cap; so that the energy exiting the end of the optical
15 fiber 18 is reflected back from the mirror. A single fiber may be
16 used in the system of Figure 1 to also conduct reflected energy
17 from the end cap or other reflective surface in the sample 22 into
18 a collection fiber 24 (shown in Figure 1 as common with the
19 excitation or illumination fiber 18). The reflected energy or
20 scattered fluorescence then is applied back to an optical splitter
21 and into a coupler 25 connected to a monochrometer 26. The output
22 of the monochrometer 26 is supplied to a computer and comparator
23 30, as one of two inputs. The other input to the comparator 30 is
24 supplied from the beam splitter 12 through an optical fiber 28.
25 Comparison of the energy launched by the laser 10 as applied to the
26 computer and comparator 30 by way of the optical fiber 28, with the

1 reflected energy supplied through the monochrometer 26 then permits
2 the desired spectroscopic analysis.

3 Systems of the type shown in Figure 1 typically use a
4 bifurcated probe of the type shown in Figure 2, which illustrates
5 in greater detail the different components of the portion of the
6 system shown in Figure 2 at the point where the excitation or
7 illumination fiber 18 and the collection or detection fiber 24
8 separate. The system of Figures 1 and 2 is very inefficient.
9 Generally, in fluorescence spectroscopy, the low Numerical Aperture
10 (NA) of si/si fiber and the solid sphere emission of fluorescence
11 from the sample 22 are incompatible. A very small portion of the
12 emitted light is collected for transmission to the monochrometer
13 26. In addition, as the probe-to-target distance is increased, the
14 divergence of the excitation radiation (12.7° half-angle for common
15 0.22 NA fiber) is high enough that energy density sufficient to
16 stimulate fluorescence rapidly drops away. Additional
17 complications also can arise in probes of the type depicted in
18 Figures 1 and 2 in that contamination and damage to the fiber
19 assembly is possible, due to the direct contact of the fibers with
20 the analyte.

21 In an effort to improve the performance of the system shown in
22 Figures 1 and 2, prior art systems have been designed as
23 illustrated in Figures 3 and 4, with a separate excitation fiber 18
24 and a number of collection fibers 24 located in a ring or circle
25 around the exterior of the collection fiber 18. Typically, these
26 fibers are housed in a steel tube 23. As shown in Figure 3, the

1 excitation fiber 18 and the collection fibers 24 may be set back
2 from the end of the tube 23. The space which is shown in Figure 3
3 then may be filled with a suitable optical plug (or quartz window)
4 to prevent contamination from the sample 22 on the ends of the
5 excitation optical fiber 18 and the ends of the collection fibers
6 24. The bundle of Figures 3 and 4 is utilized in the sample of the
7 spectroscopy system of Figure 1 in the same manner described
8 previously. While the device of Figure 3 does exhibit an improved
9 ability to collect more of the scattered light, due to numerous
10 fibers for collection surrounding the central excitation fiber, it
11 is still highly inefficient because the NA of the fibers used is
12 incompatible with the efficient delivery of excitation energy and
13 collection of highly scattered fluorescence.

14 To provide the most minimally invasive, highest flexibility,
15 lowest cost or smallest sample requirement, fibers 18 and 24 are
16 desired to be of small diameter. NA is a measure of the ability of
17 an optical fiber to gather light where $NA = \sin \theta$, where θ is the
18 maximum off-axis angle of light incident upon a fiber face that
19 will be taken up by the fiber. While high NA fibers are desirable
20 for collection of the available light from a source, such as the
21 laser 10, such high NA fibers also produce a wider angle of
22 divergence or scattering at the output end. Thus, the target,
23 either with a surgical probe or a spectrographic probe of the type
24 described in conjunction with the system of Figure 1, must be quite
25 close to the end of the fiber to achieve the energy densities
26 desired.

1 In the past, it had been considered that one way to gather the
2 maximum amount of light available from a laser source 10 into a
3 fiber was to provide a light funnel; so that large focal spots
4 could be forced into a small diameter fiber. This appeared logical
5 from considerations of water flow. While water can be channeled
6 through a small hole by way of a funnel, the rate of flow of the
7 water is greatly reduced. Similar terms have been used in optics
8 design, namely "fast" and "slow" to describe the acceptance of light
9 into a fiber, "fast" being high NA and "slow" being low NA. While
10 the expectation was that through the use of a tapered fiber, large
11 focal spots could be forced into smaller diameter fibers, tapers
12 were empirically found to be slow; they did not behave as light
13 funnels. Lenses such as the lens 14 have been used to reduce the
14 launch diameter; but such lenses increase the maximum launch angle
15 of the laser light and, consequently, increase the NA of fiber
16 required to gather that light.

17 Reference now should be made to Figures 5 and 6, which
18 illustrate in diagrammatic form, a preferred embodiment of the
19 invention. Ideally, for both surgical applications and for
20 spectroscopy applications, fiber of relatively small diameter
21 typically is desired for compatibility with the detector input.
22 This is particularly true for surgical applications where
23 relatively high flexibility of the fiber is important. As
24 mentioned previously, however, such high NA fibers typically
25 require the probe end or working end to be very close to the
26 target. This is difficult and can lead to operating device

1 failures, in surgical applications in particular. In an effort to
2 overcome the conflicting requirements of a high NA input and a low
3 NA output, the device of Figure 5 has been designed. The
4 illumination fiber 18 has an output section in the form of a
5 tapered conical fiber section having an elongated taper 32. This
6 section has a uniform taper angle along its entire length,
7 terminating at a face 34, which may be either flat or in the form
8 of a spherical or aspherical lens of small radius, as indicated in
9 Figure 5.

10 In the example shown in Figure 5, a reflective surface, in the
11 form of a mirror 36, is provided. This surface 36 is of the type
12 which would be used in a spectroscopy application of the type shown
13 generally in the system of Figure 1. The mirror 36 reflects light
14 back to a collection fiber 24, which, in the illustration of Figure
15 5, has a uniform diameter throughout its length. As illustrated in
16 Figure 5, the fibers 18 and 24, along with the tapered section 32,
17 are in physical contact with one another, and preferably are fused
18 together.

19 For a high NA input fiber 18, having for example an NA of
20 .22NA, an elongated taper 32 of approximately 16 mm in length on a
21 300 μ M core causes a .22 NA input fiber to have an output
22 divergence equivalent to a 0.055 NA fiber. This is especially
23 important in absorption spectroscopy, because a high NA, broad-
24 spectrum source is required. A high NA fiber is required to couple
25 as much light as possible into the fiber; but the high NA is a
26 problem when a large fixed sample path is required to be traversed,

1 as discussed above. If a high NA output is present, the
2 illumination light becomes too weak for gathering information at
3 even modest path lengths (1 to 2 centimeters). For example, in the
4 illustration shown in Figure 5, the distance from the end of the
5 collection fiber to the mirror 36 is one centimeter, providing an
6 overall path length of 2 centimeters.

7 By utilizing the structure illustrated in Figure 5, with a 3:1
8 taper in the tapered section 32, a ten-fold gain in efficiency is
9 obtained from the four-fold reduction or compression in the NA
10 which takes place in the tapered section 32. Similar significant
11 improvements are obtained in light scattering spectroscopy
12 applications through enhanced quantum yields and other effects.

13 Figure 6 illustrates some typical light rays and the
14 modifications which take place with these rays as they undergo the
15 NA shifting effect in the tapered section 32 of the device shown in
16 Figure 5. Each contact (bounce) a ray has with the tapered wall
17 shifts the ray to a lower angle (NA) by $2\theta_{\text{taper}}$. It should be noted
18 that a short, high ratio taper (large angle θ) will shift high
19 order modes by more (per bounce) than long low angle tapers; but
20 the maximum NA shift is limited to the highest order mode that will
21 never hit the wall of the taper, i.e., the mode with propagation
22 angle equal to θ_{taper} . In order to maximize the NA shift or
23 compression, low angle tapers are desired where the low order modes
24 make multiple bounces and the highest order mode that misses the
25 taper wall is equal to the taper angle θ_{taper} . This is the highest
26 order mode desired in the NA reduction.

1 The minimum radius r_{\min} is shown at the input end of the
2 optical fiber 18. While the length of the section of fiber 18
3 shown in Figure 6 is quite short, it is to be understood that this
4 length of fiber typically is substantially greater in length than
5 the length of the tapered section 32. For purposes of
6 illustration, however, only a short section of the fiber 18 is
7 shown in Figures 5 and 6. The tapered section 32 then has a length
8 L_{taper} which extends from the output end of the section 18 to the end
9 of the taper 34. It should be noted that the taper section 32 is
10 an integral part of the fiber 18. No gap or fusion splice is
11 required, though fusion may be used in some embodiments.

12 Two rays are traced as passing through the assembly shown in
13 Figure 6. Waveform "B" is the highest order mode which is not
14 affected by the taper (this ray does not bounce against any of the
15 taper walls). As indicated in Figure 6, this ray receives its
16 final internal reflection at the end of the fiber section 18, and
17 exits from the taper end 34 precisely at the upper edge at the face
18 34. When the ray exits into the air, it undergoes a further slight
19 upward bend at the angle of θ due to refraction; and the angle θ_{miss}
20 of the waveform B is the highest order mode which is not affected
21 by the structure, since this ray undergoes no reflections within
22 the taper 32. Examination of waveform "C" illustrates the manner
23 in which the taper 32 tends to flatten or reduce the NA of light
24 rays passing through the composite assembly. As is readily
25 apparent from an examination of the left-hand portion of Figure 6,
26 the ray C undergoes multiple relatively high-angle bounces within

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1 maximum angle that misses a bounce are only equal for a taper of
2 infinite length.

3 For a fiber 18 and taper 32 made of synthetic fused silica,
4 the refractive index is about 1.447 in the near infrared (IR) to
5 about 1.561 in the deep ultraviolet (UV). The refractive index of
6 air is taken as 1 (though this is not strictly correct); and there
7 also is a temperature dependence for the refractive index of silica
8 that varies with wavelength; although it is quite small.

9 An ideal technique for forming the tapered section 32 is to
10 form it integrally with the exit end of the illumination fiber 18.
11 This is accomplished by an "up-taper" formation in which the raw
12 material is fed into a melt zone. The fiber is rotated in a laser
13 beam to uniformly heat the circumference; and the fiber is
14 mechanically moved to remove earlier work from the interaction zone
15 with the laser beam. The technique employs surface tension to
16 drive the taper formation upward, and the freezing or solidifying
17 of the glass is accomplished through application of varying amounts
18 of heat energy. By controlling the heat and the rate at which the
19 raw material fiber is fed from below, the fiber diameter increases
20 in a non-linear rate, in that growth requires more fiber in each
21 frame or time interval as the taper is formed to yield a linear
22 taper angle. Once the final taper size and length has been
23 obtained, it is cut at its maximum diameter to form the end 34 to
24 eliminate a "tear drop" shape and leave a simple conical taper 32.
25 In fluorine-doped silica-clad silica-core fiber, the cladding is
26 conserved throughout the procedure; although some material is lost

1 to vaporization in the larger portions of the taper. The energy is
2 applied by way of a cylindrical lens, such that a line of energy
3 rather than a spot, is focused on the fiber. This serves to
4 average any fluctuation in energy and motion, so that the taper
5 walls are as smooth as possible. Other techniques for building
6 glass fiber tapers may be used, such as mechanical or laser
7 machining from rod stock or formation in a controlled furnace.
8 Ideally, the tapers should be of a uniform angle throughout its
9 length, with smooth uniform side walls to provide optimum light
10 reflection to accomplish the NA compression desired.

11 What is accomplished by the tapered output of the device shown
12 in Figures 5 and 6 is an increase in the collimation of light
13 exiting from the surface 34 of the tapered section. If, as
14 illustrated in Figure 5, the end of the taper 34 also is provided
15 with a spherical or near spherical lens surface, further focusing
16 of the output light from the end 34 is accomplished. Thus, that a
17 close approximation of collimated light is obtained and directed to
18 the mirror 36 (for absorption spectroscopy application) or toward
19 the target (for a surgical probe or fluorescence spectroscopy
20 application).

21 In the construction of an output taper of the type shown in
22 the device 18/32 of Figure 5, tapers with a 3:1 ratio and 16 mm
23 long on a 300 μ m core fiber have been produced. High NA laser
24 energy was launched into these fibers; and the output spot
25 diameters were measured at a fixed distance of 80 mm from the fiber
26 faces. The standard fiber (without a taper) gave a spot of

1 approximately 40 mm diameter, while a tapered output fiber gave a
2 spot diameter of just under 11 mm. Calculating the NA of these
3 outputs gave 0.24 for the standard fiber (published NA is $0.22 \pm$
4 0.02) and 0.06 for the tapered output. This is a four-fold
5 reduction or compression in NA.

6 For surgical applications, such as coagulation of tissue in a
7 gastro-intestinal medical application, the assembly shown in
8 Figure 7 may be constructed. As illustrated in Figure 7, the input
9 optical fiber 18 is integrally connected physically and optically
10 with a tapered section 32. This section 32 is encased in a fused
11 quartz ferrule 40; and the end of the tapered section 32 is
12 integrally formed with a lens surface 44, or has a lens surface 44
13 added to it. The combination of the lens surface 44 and the
14 operation of the taper 32 serves to produce a nearly collimated
15 (low NA) output. For a hypothetical coagulation procedure, if a 2
16 mm or smaller spot is required to generate the desired effect, the
17 3:1 up-taper on 300 μm core fiber previously described may be held
18 as far as 10 mm from the target tissue as opposed to a maximum of
19 3.8 mm for a standard 300 μm core fiber. Thus, the probe of Figure
20 7 is ideal.

21 Figure 8 is a diagrammatic representation in partial cross
22 section of an absorption/transmission spectroscopy probe utilizing
23 a single-taper construction as illustrated in Figure 5 for the
24 parts 18, 32 and 34. The single fiber construction shown in Figure
25 9 employs a steel or polymer housing 50 about the taper 32, which
26 may be contained within a quartz ferrule 40 of the type shown in

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1 surrounding a central excitation or illumination fiber 18. All of
2 these fibers can terminate in a probe of the type shown in Figure
3 9; and the excitation fiber 18 preferably terminates in an up-
4 tapered section 32 of the type shown in Figure 5. The ring of
5 collection fibers may be simple, straight or taper ended fibers.
6 The orientation of the fibers at the input ends and at the output
7 ends are illustrated in the diagrammatic circles located at the
8 right-hand end and the left-hand end of the multiple fiber probe
9 shown in Figure 10.

10 Figure 11 is a diagrammatic representation of a variation of
11 the device shown in Figure 5, in which the illumination fiber
12 combination including the optical fiber 18 and the up-tapered
13 section 32 terminate in a common face 62, with the input of a down-
14 tapered collection fiber combination including a tapered section 60
15 and the collection fiber 24, of the type illustrated in Figure 9,
16 for example. As illustrated in Figure 11, a common lens surface 62
17 is provided to cause overlap of the light exiting from the up-
18 tapered section 32 and the insertion cone of the down-tapered
19 section 60 of the collection fiber 24. With sufficient NA
20 compression or reduction effected by the tapered section 32, a lens
21 such as the lens 62 may not be necessary; but the lens does improve
22 the amount of overlap which takes place. By employing the down-
23 tapered section 60 on the collection fiber 24, improved collection
24 of the available reflected light when the device of Figure 11 is
25 used in various types of spectrographic systems is achieved over
26 the prior art devices which are shown and described above in

1 conjunction with Figure 3 and 4.

2 Figures 12 and 13 comprise a side cross-sectional view and an
3 end view, respectively, of a modification of the prior art device
4 of Figures 3 and 4, which incorporates applicant's preferred
5 embodiment of the invention. A central illumination fiber
6 terminates in an up-tapered section 32, which is shown most clearly
7 in the end view of Figure 13. This section is surrounded by a
8 plurality of down-tapered sections 60, which are coupled to
9 corresponding collection fibers 24. The entire assembly is housed
10 within a quartz ferrule 70, which has a threaded external portion
11 72 on it. As illustrated in Figure 12, a lens 62 of the type shown
12 in Figure 11 is placed or formed on the device. The desirable
13 effects of surrounding the illumination or excitation taper 32 with
14 a plurality of tapered collection fibers 60 results in improved
15 operating characteristics over the device of Figures 3 and 4. The
16 fiber array using multiple (six as shown in Figure 13) collection
17 fibers represents what may be considered to be an ultimate design
18 for use in many spectroscopy applications.

19 The advantages which are obtained with the devices of Figures
20 5 through 13 are particularly significant, for example, when the
21 surgical probe of Figure 7 is considered. In surgical applications
22 using a single fiber, the reduced divergence of the output which is
23 obtained from the use of the up-tapered (NA reduction) conical
24 section 32 permits maintenance of minimum therapeutic energy
25 densities at considerably larger separation distances than was
26 possible with prior art devices. For example, in free-beam (normal

1 flat polish on unmodified optical fiber) surgical fibers, 0.22 NA
2 and 300 μ m core diameter, if the surgeon must maintain a spot of 3
3 mm diameter to obtain therapeutic effectiveness but cannot drop
4 below 2 mm diameter or the tissue chars and damages the fiber, the
5 fiber tip must be maintained between 1.6 and 6 mm from the tissue.
6 While this does not seem too difficult on initial examination, in
7 reality if the fiber is held near the close limit of the tissue,
8 spattering tissues (blood, fat, connective tissue) quickly cover
9 the fiber output and burn. Damage to the fiber then results. For
10 a 3:1 NA reduction taper on the same fiber, the operational
11 separation distance becomes 1 mm to 19 mm. This is huge by
12 comparison with the distance which could be tolerated with the
13 prior art device.

14 In addition, for illumination applications in medicine
15 (including UV curing of dental adhesives), single fiber tapers such
16 as the one shown in Figure 7, can serve to deliver more intense
17 spots of light through endoscopes without the additional diameter
18 requirements of conventional lens systems.

19 The foregoing description of the preferred embodiment of the
20 invention should be taken as illustrative, and not as limiting.
21 Various changes will occur to those skilled in the art for
22 performing substantially the same function, in substantially the
23 same way, to achieve substantially the same result, without
24 departing from the true scope of the invention as defined in the
25 appended claims.
26

WHAT IS CLAIMED IS

1. An optical fiber with Numerical Aperture (NA) compression comprising:

a tapered fiber section of a predetermined length having a light input end of a first predetermined diameter and having a light output end of a second predetermined diameter greater than said first predetermined diameter.

2. The combination according to Claim 1 wherein said tapered fiber section has a uniform taper from the light input end thereof to the light output end thereof.

3. The combination according to Claim 2 wherein said tapered fiber section has a generally conical shape.

4. The combination according to Claim 1 wherein said tapered fiber section has a generally conical shape.

1 5. An optical fiber with Numerical Aperture (NA) compression
2 including in combination:

3 a first fiber section having a light input end and a
4 light output end and having a first predetermined diameter; and

5 a tapered fiber section of a predetermined length having
6 an input end of said first predetermined diameter optically coupled
7 with the output end of said first fiber section and having an
8 output end of a second predetermined diameter greater than said
9 first predetermined diameter.

10
11 6. The combination according to Claim 5 wherein said tapered
12 fiber section has a uniform taper from the light input end thereof
13 to the light output end thereof.

14
15 7. The combination according to Claim 6 wherein said tapered
16 fiber section has a generally conical shape.

17
18 8. The combination according to Claim 7 wherein said first
19 end of said tapered fiber section is physically coupled with the
20 output end of said first fiber section.

21
22 9. The combination according to Claim 8 wherein said tapered
23 fiber section is integrally formed with said first fiber section on
24 the output end thereof.

1 10. The combination according to Claim 9 wherein said first
2 fiber section and said tapered fiber section comprise glass fibers.

3
4 11. The combination according to Claim 10 wherein the taper
5 of said tapered fiber section from the input end thereof to the
6 output end thereof is at least 3:1.

7
8 12. The combination according to Claim 11 further including
9 a collimating lens on the output end of said tapered fiber section.

10
11 13. The combination according to Claim 5 wherein said tapered
12 fiber section has a uniform taper angle θ .

13
14 14. The combination according to Claim 13 wherein said
15 tapered fiber section has a generally conical shape.

16
17 15. The combination according to Claim 5 wherein said first
18 end of said tapered fiber section is physically coupled with the
19 output end of said first fiber section.

20
21 16. The combination according to Claim 15 wherein said first
22 fiber section and said tapered fiber section comprise glass fibers.

23
24 17. The combination according to Claim 16 wherein said
25 tapered fiber section has a generally conical shape.

26

1 18. The combination according to Claim 5 wherein said tapered
2 fiber section has a generally conical shape.

3
4 19. The combination according to Claim 5 wherein said tapered
5 fiber section is integrally formed with said first fiber section on
6 the output end thereof.

7
8 20. The combination according to Claim 5 further including a
9 collimating lens on the output end of said tapered fiber section.

10
11 21. The combination according to Claim 5 wherein said first
12 fiber section and said tapered fiber section comprise glass fibers.

13
14 22. An optical fiber assembly with Numerical Aperture (NA)
15 compression including in combination:

16 an illumination fiber section having a light input end
17 and a light output end and having a first predetermined diameter;

18 a first tapered fiber section of a predetermined length
19 with an input end of said first predetermined diameter optically
20 coupled with the output end of said first fiber section, and having
21 an output end of a second predetermined diameter greater than said
22 first predetermined diameter;

23 a collection fiber section having a light input end and
24 a light output end, said collection fiber section physically
25 located with the light input end thereof adjacent the light output
26 end of said tapered fiber section.

1 23. The combination according to Claim 22 wherein said output
2 end of said illumination fiber section is physically and optically
3 coupled with the input end of said first tapered section.

4
5 24. The combination according to Claim 22 wherein said
6 collection fiber section is a second tapered fiber section, and the
7 light output end of said second tapered fiber section has a second
8 predetermined diameter, and the light input end of said second
9 tapered fiber section has a third predetermined diameter greater
10 than said second predetermined diameter.

11
12 25. The combination according to Claim 24 wherein said
13 illumination fiber section, said first tapered fiber section and
14 said collection fiber section all comprise glass fiber material.

15
16 26. The combination according to Claim 25 wherein said
17 collection fiber section comprises a plurality of substantially
18 identical collection fiber sections.

19
20 27. The combination according to Claim 26 wherein said
21 plurality of collection fiber sections are physically arranged with
22 the light input ends thereof around said first tapered fiber
23 section.

1 28. The combination according to Claim 27 wherein the output
2 of said first tapered fiber section and the input ends of said
3 collection fiber sections are fused to one another.

4
5 29. The combination according to Claim 28 wherein said output
6 end of said illumination fiber section is physically and optically
7 coupled with the input end of said first tapered section.

8
9 30. The combination according to Claim 22 wherein said
10 illumination fiber section, said first tapered fiber section and
11 said collection fiber section all comprise glass fiber material.

12
13 31. The combination according to Claim 22 wherein said
14 collection fiber section comprises a plurality of substantially
15 identical collection fiber sections.

16
17 32. The combination according to Claim 31 wherein said
18 plurality of collection fiber sections are physically arranged with
19 the light input ends thereof around said first tapered fiber
20 section.

21
22 33. The combination according to Claim 32 wherein the output
23 of said first tapered fiber section and the input ends of said
24 collection fiber sections are fused to one another.

25
26

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34. The combination according to Claim 22 wherein said plurality of collection fiber sections are physically arranged with the light input ends thereof around said first tapered fiber section.

ABSTRACT

A fiber optic probe of the type typically used in medical instruments includes an illumination optical fiber having a relatively high Numerical Aperture (NA) for coupling as much light as possible into the fiber at its input end. At the output end, an outwardly flared uniform taper is provided to increase collimation of the light exiting from the illumination end, thereby causing the Numerical Aperture (NA) at the output end of the illumination fiber to be a lower NA than that at the input end. For optical spectroscopy applications, collection fibers are located in close proximity to or surrounding the tapered output end of the illumination fiber for collecting reflected or scattered light rays from a target for use in qualitative and quantitative analysis of material.

FIG. 1

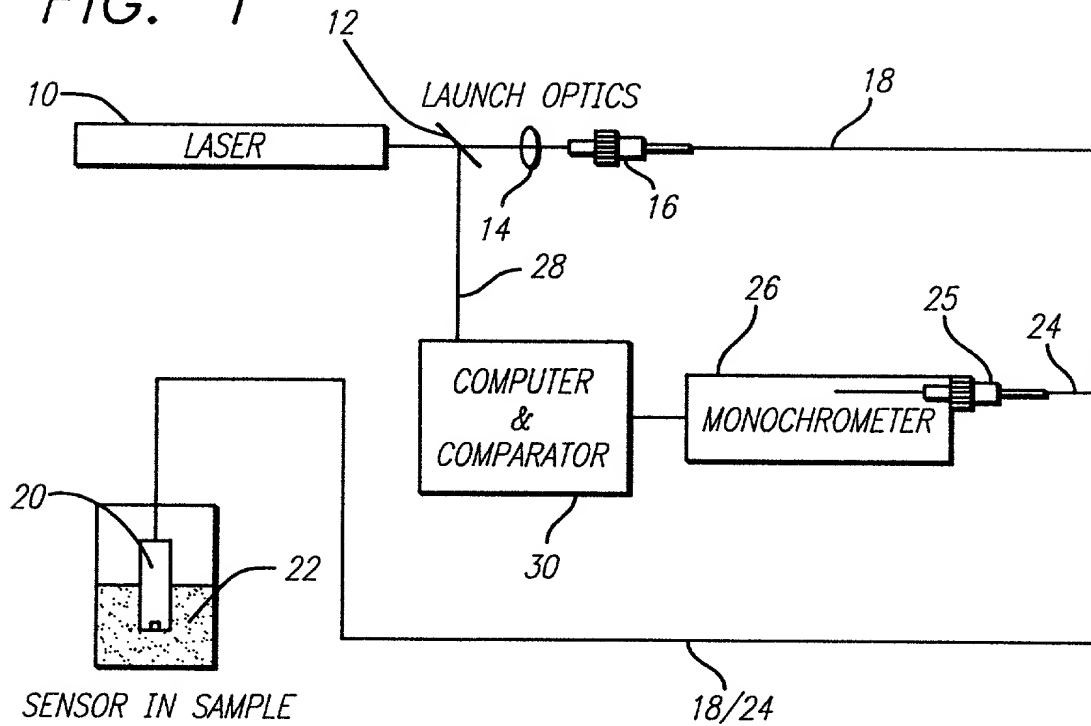


FIG. 2

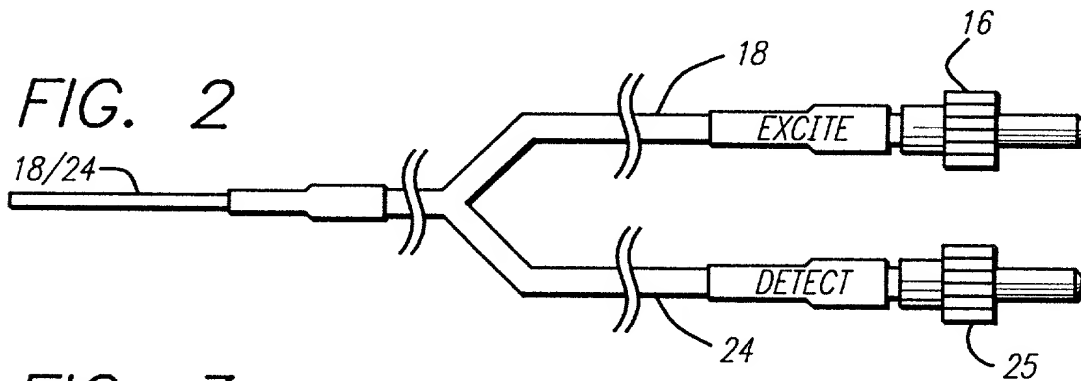


FIG. 3

PRIOR ART

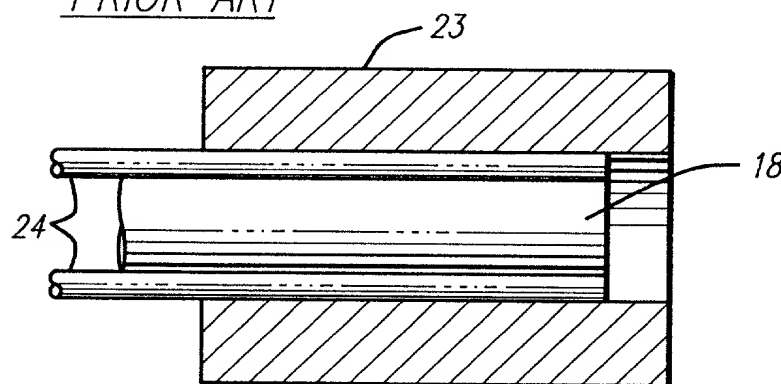


FIG. 4

PRIOR ART

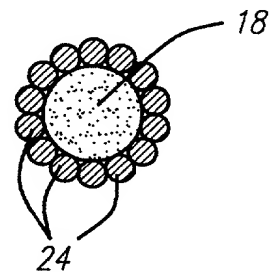


FIG. 5

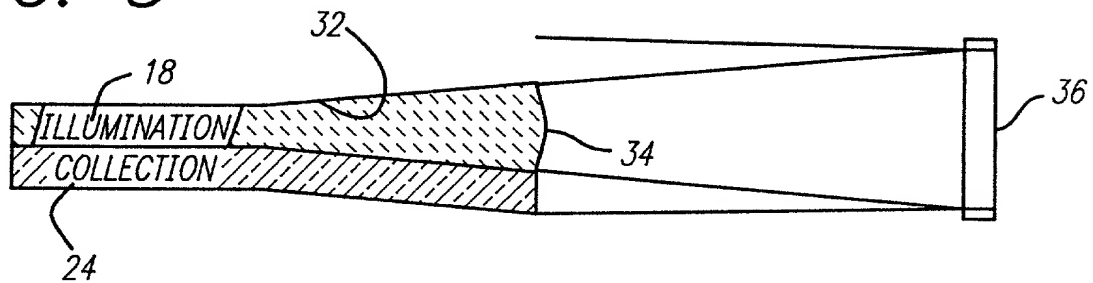


FIG. 6

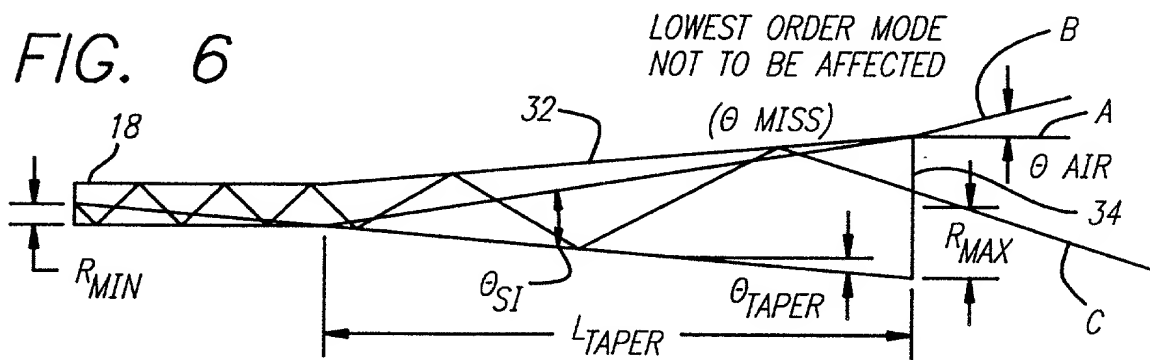


FIG. 7

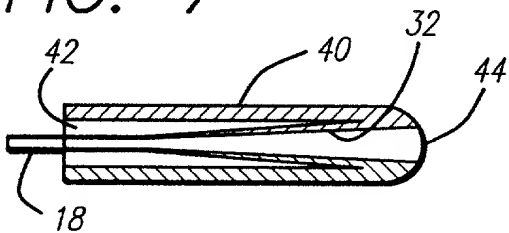


FIG. 8

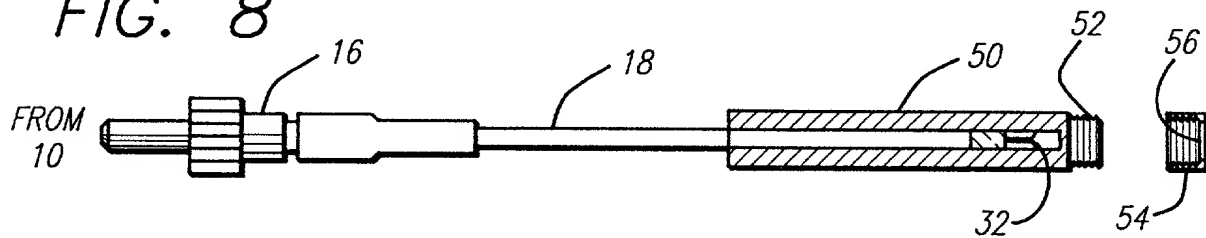


FIG. 9

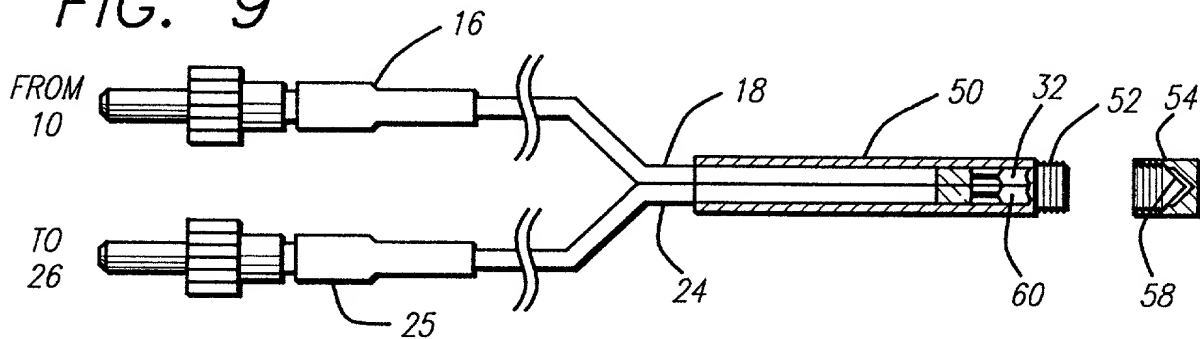


FIG. 10

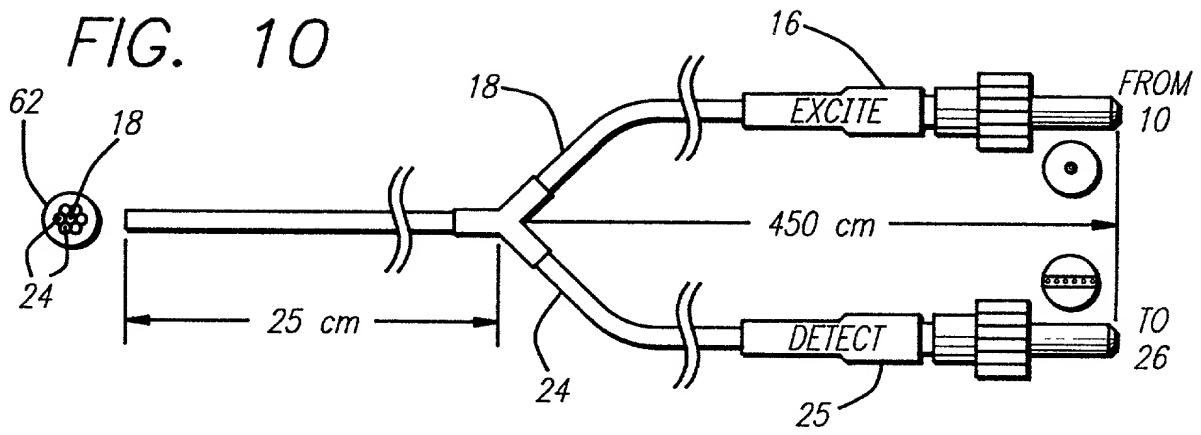


FIG. 11

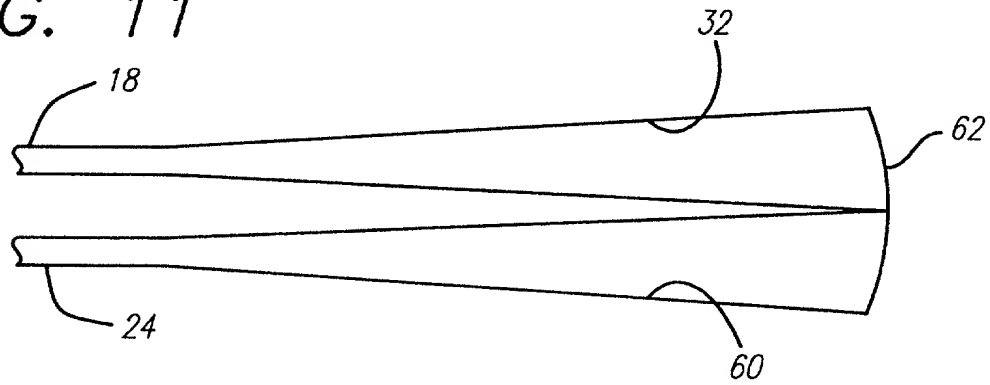


FIG. 12

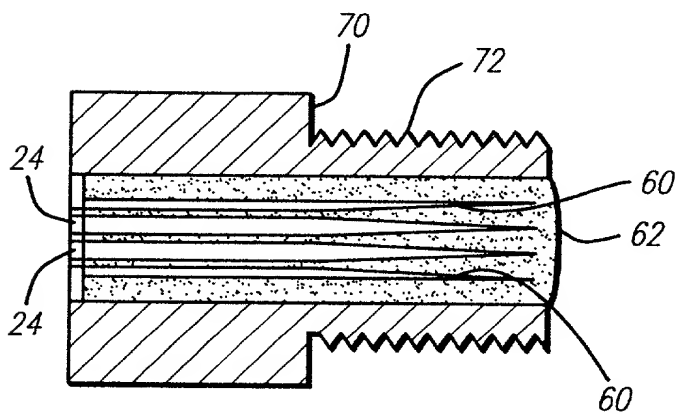
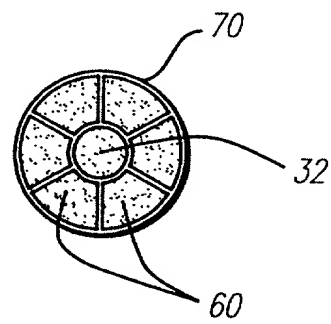


FIG. 13



Attorney's Docket No. 4990.21

PATENT

Applicant or Patentee: Stephen Griffin

Application or Patent No.: /

Filed or Issued:

For: OPTICAL FIBER WITH NUMERICAL APERTURE COMPRESSION

**VERIFIED STATEMENT (DECLARATION) CLAIMING SMALL ENTITY
STATUS (37 CFR 1.9(f) and 1.27(b))—INDEPENDENT INVENTOR**

As a below named inventor, I hereby declare that I qualify as an independent inventor, as defined in 37 CFR 1.9(c), for purposes of paying reduced fees under Sections 41(a) and (b) of Title 35, United States Code, to the Patent and Trademark Office with regard to the invention entitled OPTICAL FIBER WITH NUMERICAL APERTURE COMPRESSION described in

- ☒ the specification filed herewith.
- ☐ application no. / , filed .
- ☐ patent no. , issued .

I have not assigned, granted, conveyed or licensed, and am under no obligation under contract or law to assign, grant, convey or license, any rights in the invention to any person who could not be classified as an independent inventor under 37 CFR 1.9(c), if that person had made the invention, or to any concern that would not qualify as a small business concern under 37 CFR 1.9(d), or a nonprofit organization under 37 CFR 1.9(e).

Each person, concern or organization to which I have assigned, granted, conveyed, or licensed or am under an obligation under contract or law to assign, grant, convey, or license any rights in the invention is listed below:

- ☒ no such person, concern, or organization.
- ☐ persons, concerns or organizations listed below *

*NOTE: Separate verified statements are required from each named person, concern or organization having rights to the invention averring to their status as small entities. (37 CFR 1.27)

FULL NAME

ADDRESS

☐ INDIVIDUAL ☐ SMALL BUSINESS CONCERN ☐ NONPROFIT ORGANIZATION

FULL NAME

ADDRESS

☐ INDIVIDUAL ☐ SMALL BUSINESS CONCERN ☐ NONPROFIT ORGANIZATION

FULL NAME

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I acknowledge the duty to file, in this application or patent, notification of any change in status resulting in loss of entitlement to small entity status prior to paying, or at the time of paying, the earliest of the issue fee or any maintenance fee due after the date on which status as a small entity is no longer appropriate. (37 CFR 1.28(b))

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further, that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application, any patent issuing thereon, or any patent to which this verified statement is directed.

Stephen Griffin

Name of inventor

Stephen Griffin

Date

8/13/98

Signature of Inventor

Stephen Griffin

Name of inventor

Date

Signature of Inventor

Name of inventor

Date

Signature of Inventor

DECLARATION FOR PATENT APPLICATION

DOCKET NUMBER
4990.21

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

OPTICAL FIBER WITH NUMERICAL APERTURE COMPRESSION, the specification of which is attached hereto unless the following box is checked:

☐ was filed on _____ as United States Application Number or PCT International Application Number _____ and was amended on _____ (if applicable).

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56.

I hereby claim foreign priority benefits under Title 35, United States Code, §119(a)-(d) of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed.

Prior Foreign Application(s)

Priority Claimed
☐ Yes ☐ No

(Number) (Country) (Day/Mo/Year Filed)

☐ Yes ☐ No

(Number) (Country) (Day/Mo/Year Filed)

I hereby claim the benefit under Title 35, United States Code, §119(e) of any United States provisional application(s) listed below.

(Application Number) (Filing Date)

(Application Number) (Filing Date)

I hereby claim the benefit under Title 35, United States Code, §120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, §112, I acknowledge the duty to disclose information which is material to patentability as defined in Title 37, Code of Federal Regulations, §1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

(Application No.) (Filing Date) (Status- patented, pending, abandoned)

(Application No.) (Filing Date) (Status- patented, pending, abandoned)

I hereby appoint the following attorney and/or agent to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of sole or first inventor (given name, family name) Stephen Griffin

Inventor's signature Stephen Griffin Date 8/3/92Residence Phoenix, Arizona Citizenship USAPost Office Address 3437 E. Melody Drive, Phoenix, Arizona 85040☐ Additional inventors are being named on separately numbered sheets attached hereto.